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Utilization of fly ash and ground granulated blast furnace slag as an alternative silica source in reactive powder concrete

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ABSTRACT

Reactive powder concrete (RPC) is an ultra high strength cement-based material. Cement and silica fume (SF) content of RPC are generally rather high compared to the conventional concrete. The aim of this study is to decrease the cement and SF content of RPC using with fly ash (FA) and/or ground granulated blast furnace slag (GGBFS). The effect of these mineral admixtures on compressive strength of RPC has been investigated under autoclave curing. In the first stage, the effect of autoclave time and SF content on compressive strength was determined. In the second stage, SF was gradually decreased and cement was replaced with FA and/or GGBFS at different proportions. The microstructure was investigated by scanning electron microscope (SEM). Test results indicate that, the utilization of FA and/or GGBFS in RPC is possible without significant mechanical performance loss. SEM micrographs revealed the tobermorite having different morphology.

1. Introduction

Reactive powder concrete (RPC) is a rather new cement-based material developed through microstructural engineering. Conventional RPC is composed of cement and very fine powders such as crushed quartz and silica fume. The basic principles for the development of RPC have been explained by the Richard and Cheyrezy [1,2].

Cement dosage of RPC is generally over 800–1000 kg/m^3. A high amount of cement not only affects the production costs, but also has negative effects on the heat of hydration and may cause shrinkage problems. Replacing cement with mineral admixtures seems to be a feasible solution to these problems. Furthermore, incorporation of mineral admixtures may positively affect the durability of concrete. Kejin and Zhi [3] showed that the maximum heat of cement hydration in binary/ternary cement (fly ash and/or ground granulated blast furnace slag) concrete decreased with supplementary cementitious material replacements.

Massidda et al. [4] studied the effects of autoclaving under saturated vapor at 180 °C on the physical and mechanical properties of reactive-powder mortars reinforced with brass coated steel fibers. Autoclave curing yielded flexural strength of 30 MPa and compressive strength of 200 MPa. Shaheen and Shrive [5] investigated freeze–thaw resistance of RPC. Test results showed that RPC has excellent freeze–thaw resistance with no sign of damage up to 600 cycles according to ASTM C 666 test procedure. Rougeau and Borys [6] showed that ultra high performance concrete (UHPC) can be produced with ultra fine particles other than SF such as fly ash, limestone microfiller or metakaolin. Lee et al. [7] showed that RPC has a good repair and retrofit potentials on compressive and flexural strengthening. The effects of compressive and flexural strengthening with bonding RPC of 10-mm thickness are about 200% and 150% more than those of normal strength concrete. Chan and Chu [8] reported that incorporation of silica fume in RPC matrix remarkably enhances the steel fiber–matrix bond characteristics due to the interfacial-toughening effect upon fiber slip.

In this study, cement was replaced with mineral admixtures (FA and/or GGBFS) at different proportions. The amount of SF was also reduced using with mineral admixtures which are alternative external silica source for autoclaving. Quartz was used as an aggregate. Test results were presented comparatively with the mixtures having constant SF.

2. Experimental

Quartz with different sizes (0–0.4, 0.5–1.0 and 1.0–3.0 mm) was used as a fine aggregate. The specific gravity of quartz is 2.65. A polycarboxylate based superplasticizer (SP) is in conformity with ASTM C 494-81, type F was used in this study. The physical, chemical and mechanical properties of Portland cement (CEM I 42,5), properties of silica fume, fly ash and slag are presented in Table 1. Furthermore, brass coated steel fibers (3% by volume) 6 mm long with the diameter of 0.15 mm were used to improve the ductility of RPC and to prevent explosive degrading under compression. The aspect ratio and tensile strength of the fiber are 40 and

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Table 1
Physical, chemical and mechanical properties of cement, silica fume, fly ash and slag

	Cement	Silica fume (SF)	Fly ash (FA)	Slag (GGBFS)
Chemical composition (%)				
SiO_2	20.10	92.26	42.10	39.66
Al_2O_3	5.62	0.89	19.40	12.94
Fe_2O_3	2.17	1.97	4.60	1.58
CaO	62.92	0.49	27.00	34.20
MgO	1.14	0.96	1.80	6.94
Na_2O	0.30	0.42	–	0.20
K_2O	0.85	1.31	1.10	1.44
SO_3	2.92	0.33	2.40	0.72
Cl^-	0.001	0.09	–	–
L.O.I.	3.84	–	1.30	1.20
I.R.	0.63	–	–	–
F.CaO (%)	0.52	–	4.30	–
Physical properties of cement				
Specific gravity				3.13
Initial setting time (min)				130
Final setting time (min)				210
Volume expansion (mm)				1.00
Specific surface (m^2/kg)				
Cement (Blaine)				380
SF (Nitrogen Ab.)				20 000
FA (Blaine)				290
GGBFS (Blaine)				396
Compressive strength of cement (MPa)				
2 days				29.9
7 days				43.2
28 days				51.9

2250 MPa, respectively. Various mixture designs with different SF, FA, GGBFS contents are presented in Tables 2–5. Abbreviations SF, F and G in tables and figures shows silica fume, fly ash and ground granulated blast furnace slag, respectively. SF, FA or GGBFS ratios by cement weight were also given in the abbreviations. For instance, G10F30 means cement was replaced with 10% GGBFS and 30% FA.

The mixtures were mixed in a high speed mixer and compacted by hand operations and vibration. Initially dry powders (cement, SF, FA and GGBFS) and aggregates (quartz) were mixed at low speed for about 1 min. And, mixture was mixed at low and high speed for about 2 min. Water and SP was added to premixed composition and mixture remixed at high speed for about 5 min. Finally, steel fibers were added and mixed at high speed for about 2 min. The specimens were kept in the molds for 16 h at room temperature of about 20 °C. After demolding, specimens were autoclaved at 210 °C under 2.0 MPa pressure for 8 h. Temperature and pressure have reached to their maximum values in 2.5 h. Finally, specimens were kept in laboratory conditions for cooling.

The compressive strength tests were employed on $50 \times 50 \times 50$ mm cube specimens. Furthermore, external pressure was applied on some mixtures during setting and hardening. In this case, special 100×100 mm cylindrical molds having high rigidity were used.

Table 2
Composition and properties of the mixtures in SF content investigation

Material	SF0	SF10	SF20	SF25	SF30	SF35	SF40	SF45
Cement (kg/m^3)	830	830	830	830	830	830	830	830
SF (kg/m^3)	0	83	166	208	249	291	332	374
1–3 mm quartz (kg/m^3)	660	611	562	538	513	489	464	439
0.5–1 mm quartz (kg/m^3)	328	304	280	268	256	244	232	219
0–0.4 mm quartz (kg/m^3)	328	304	280	268	256	244	232	219
Water (kg/m^3)	151	151	151	151	151	151	151	151
SP (L/m^3)	32	38	44	50	53	55	57	59
Water from SP	19	23	26	30	32	33	34	35
Water/cement	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Water/powder	0.18	0.17	0.15	0.15	0.14	0.13	0.13	0.13
Water/powder[a]	0.20	0.19	0.18	0.17	0.17	0.16	0.16	0.15
Steel fiber (kg/m^3)	234	234	234	234	234	234	234	234
Flow table (mm)	110	112	112	115	115	115	116	118
Molar CaO/SiO_2	3.38	2.32	1.77	1.58	1.43	1.30	1.20	1.11
Compressive strength (MPa)	171	204	239	249	250	259	248	246

[a] Calculated with total water (water + water from SP).

Table 3
FA or GGBFS replacement (SF constant)

Material	CTRL	F20	F40	F60	G20	G40	G60
Cement (kg/m^3)	830	664	498	332	664	498	332
SF (kg/m^3)	291	291	291	291	291	291	291
Mineral admixture (kg/m^3)	—	166	332	498	166	332	498
1–3 mm quartz (kg/m^3)	489	460	431	402	481	473	465
0.5–1 mm quartz (kg/m^3)	244	230	215	201	240	236	232
0–0.4 mm quartz (kg/m^3)	244	230	215	201	240	236	232
Water (kg/m^3)	151	151	151	151	151	151	151
SP (L/ m^3)	55	58	62	65	55	55	55
Water from SP	33	35	37	39	33	33	33
Water/cement	0.18	0.23	0.30	0.45	0.23	0.30	0.45
Water/powder	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Water/powder[a]	0.16	0.17	0.17	0.17	0.16	0.16	0.16
Steel fiber (kg/m^3)	234	234	234	234	234	234	234
Flow table (mm)	115	114	114	110	115	117	117
Molar CaO/SiO_2	1.30	1.08	0.85	0.67	1.11	0.94	0.78

[a] Calculated with total water (water + water from SP).

3. Results and discussion

Test results were presented in the following paragraphs:

3.1. Influence of the autoclaving duration time and SF content on the compressive strength of RPC

In the first stage, optimum autoclaving time under 2.0 MPa pressure and 210 °C has been determined related to the compressive strength. For this purposes SF30 mixture presented in Table 2 has been tried for 4, 8 and 12 h under autoclave curing. The average compressive strength values were 239, 253 and 260 MPa, after 4, 8 and 12 h, respectively. Eight hours of curing period was selected for further studies since increasing rate of compressive strength beyond 8 h was negligible.

The relationship between the compressive strength of 8-hour autoclaved RPC versus SF content is shown in Table 2. The mixture designs are also presented in Table 2. It may be seen from the Table 2 that SF content affected the compressive strength of RPC dramatically. The compressive strength of SF35 mixture reached up to 259 MPa. This value is 51% higher than the control mixture which has only cement as a binder. The molar CaO/SiO_2 ratio which is important under autoclaving to achieve maximum strength is 1.30 for the SF35 mixture. It can be seen from Table 2 molar CaO/SiO_2 ratio decreases with increasing amount of SF which increased the compressive strength considerably up to a limit. Beyond the specific value, increasing the SF content decreased the compressive strength slightly which means some excessive SF remains in the system showing no reaction. In other words there is an optimum molar CaO/SiO_2 ratio giving maximum strength for each mixture. Furthermore, the hydration of the cement under autoclave is quite different. Under the conditions of high temperature and pressure, the chemistry of hydration is substantially altered. In the hydration of tricalcium silicate (C_3S) and dicalcium silicate (C_2S), in the absence of an external SiO_2 source, crystalline α-dicalcium silicate hydrate is formed instead of an amorphous calcium silicate hydrate (CSH) phase. Tricalcium aluminate (C_3A) and tetracalcium alumino-ferrite (C_4AF) yield a hydrogarnet phase.